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A Digital Temperature Control and Measurement System

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R. B. Strem, B. K. Das, W. T. Angel,
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A Digital Temperature Control
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ABSTRACT

We describe an automated digital temperature control and measurement system with a temperature resolution of 0.3 to 3.0 mK and operating in the temperature range -40°C to +70°C.

I. INTRODUCTION

In our work on the thermodynamic properties of condensed phases, we must vary temperature in steps, controlling the temperature to a millidegree for as long as days at a time, until thermodynamic equilibrium is attained. It has been our practice to use analog controllers[1-5] to control our liquid baths, vacuum thermostats, and layered thermostats. With the appearance of inexpensive microcomputers, it now becomes feasible to construct a dedicated digital temperature control and measurement system. Such a controller can regulate and step the temperature automatically, while the computer also collects the data from the experimental transducers. The IEEE-488 interface bus[6] makes the hardware assembly straightforward; this bus is becoming ever more prevalent and its price is declining. The software has also been designed in a simple way, avoiding the more sophisticated approaches to such a "discrete-time" control system.[7,8]

We have built a digital temperature measurement and control and data acquisition system with proportional and integral temperature control.[7] With our vacuum thermostat and auxiliary cooler, we can control and measure temperature between -40°C and +70°C with an accuracy of 3 mK and a precision as small as 0.3 mK.

II. HARDWARE

A. Thermostat

Temperature control of better than a millidegree cannot be achieved without attention to the design of the thermostat itself. For a multistage vacuum thermostat, we require the minimization of heat transfer between stages and the maximization of heat transfer within each stage. To minimize transfer between stages, we evacuate the insulating space, we use materials of low thermal conductivity when we connect the stages, and we thermally ground all wires passing from stage to stage. To maximize thermal conductivity within a stage, we use materials of high thermal conductivity.

These principles are illustrated in the design of our vacuum thermostat, shown in Figure 1. The thermostat consists of an outer vacuum can (A), an inner can (radiation shield) (B) and the experimental stage (C). The two cans are evacuated independently through vacuum lines D. The vacuum lines and the connections between stages, E and F, are made of thin-walled stainless-steel tubing. Vacuum connections, indicated by closed circles, are made with elastomer o-rings.[9,10]

The outer vacuum can A is made entirely of aluminum, which provides good thermal conductivity with minimal weight. Around the outer can is wrapped a 3/8" o.d. aluminum

tubing at one turn per inch. The first stage of temperature control is a commercial cooler-circulator[11] which controls the temperature of a circulating fluid to 0.02 K and pumps the fluid through the aluminum tubing.

The second stage, radiation shield B, is made entirely of copper. A heater wire of #32 manganin wire with a total resistance of 338Ω is wrapped in grooves (6 turns/in.) around the can and cemented with GE7031 varnish.

The experimental stage C is also made of copper. Experimental transducers may be mounted on the upper and lower surfaces of this stage.

Electrical leads for thermometers, heaters, thermocouples, etc. enter the thermostat through the vacuum lines D from a vacuum feed-through at the top of the vacuum lines. These wires, #30 enameled copper, are thermally grounded at E and F. The high-frequency feed-throughs necessary for certain of our experiments are coaxial SMA feed-throughs, mounted on flanges G and H.

A vacuum of about 10^{-3} mmHg is maintained in the thermostat by means of a mechanical pump and a diffusion pump.

We estimate the total heat transfer from the interior of the thermostat to the cooler by radiation and conduction to be about 1 W when the vacuum can A is at 200K and the radiation shield and experimental stage are at 273 K.

An alternate design which we also use has all OFHC copper stages and indium o-rings. It is more expensive to build and more awkward to open and close, but has a particularly small out-gassing rate after a 100°C baking (less than 0.5 μHg per day). It can therefore be disconnected from its vacuum pump for prolonged periods to minimize mechanical vibrations.

B. Thermometry

The thermometers are a 100Ω platinum thermometer (T1), mounted on the experimental stage C, and a thermistor (T2), mounted on the top flange H of the shield stage. The thermometer circuits are shown in Fig. 2. Each thermometer is in series with a standard resistor (R1 and R2) and a mercury battery. If R_T is the resistance of the thermometer, V_T the voltage drop across the thermometer, and V_S the voltage drop across the standard resistor, then $R_T = (V_T/V_S)R_S$. The thermistor is a bead thermistor[12] with an expected stability of 0.05% (or 13 mK) per year. The standard resistors[13] have a temperature coefficient of 1 ppm/K and a stability of 5 ppm/year. V_T and V_S are measured by a 6 1/2-digit voltmeter.

The platinum thermometer was calibrated to 1 mK by the National Bureau of Standards on the International Practical Temperature Scale of 1968. The thermistor was calibrated with respect to the platinum thermometer. Polynomial least squares fits were obtained of $T(R_T)$ for the platinum thermometer and of $T(\ln R_T)$ for the thermistor[14-15] With a voltage resolution of 1 μV, we can resolve 3 mK on the platinum thermometer and 0.3 mK on the thermistor. A second thermistor, mounted on the experimental stage, could easily be added to obtain the maximum temperature resolution.

C. Feedback loop

Figure 2 is a block diagram of the hardware for the feedback loop. A scanner[16] (multiplexer) allows us to read all the thermometer voltage with one voltmeter.[17] Both the scanner and the voltmeter are under the control of the microcomputer.[18] The computer calculates the inner stage and experimental stage temperatures from the voltages, using the calibration equations. The temperature of the inner stage is compared to the desired temperature and the difference used to adjust the heater voltage by means of a digital-to-analog (D/A) converter[19] and a programmable power supply.[20]

The scanner, voltmeter, and D/A converter all connect to the computer via the IEEE-488 interface bus.[21]

III. SOFTWARE

A. General

The computer brings the shield stage temperature to a desired value and controls it at that temperature until the experimental stage reaches that same temperature (within a given discrepancy) and remains so for a given time. Then the computer collects the experimental data, which are voltages on the other channels of the scanner (not shown in Fig. 2). The computer repeats the data collection a number of times and calculates a standard deviation for each voltage. During the data collection, the shield is not under temperature control, but the experimental stage is so isolated from the shield that any drift does not reach the experimental stage during the short time of the data collection (a few minutes). The data are recorded on a printer which is connected to the computer by a IEEE-488-to-RS232 converter[21] and on a cassette tape. Then the computer increments the temperature and repeats the procedure given above.

B. Feedback loop

The feedback control consists of integral and proportional control[7,8] of the shield temperature. The experimental stage temperature follows the shield temperature, mainly by gas conduction.

We use the following symbols:

T_A = Ambient temperature of vacuum can

T_D = Desired temperature of radiation shield and experimental stage

T_S = Actual temperature of radiation shield

T_E = Actual temperature of experimental stage

The "integral" control provides for most of the power required to the radiation shield heater to <u>maintain</u> a given difference between T_A and T_D. The power to the heater is proportional to the square of the heater voltage. We designate this "steady-state voltage" by V_{SS} and write

$$V_{SS}^2 \approx A_I (T_D - T_A) \tag{1}$$

where A_I is a constant. A_I can be determined empirically or estimated from the calculated heat loss. The functional relationship between V_{SS} and $(T_D - T_A)$ may be more complex than equation (1), but equation (1) is an adequate first approximation.

The "proportional" control provides the power to <u>attain</u> T_D when T_S is less than T_D. If V_p is the needed heater

voltage, then

$$V_p^2 = A_p (T_D - T_S) \qquad (2)$$

If we consider this contribution to be primarily the heating of the shield itself, ignoring the slow radiation loss to the experimental stage, then to a first approximation

$$A_p \approx RC_p/t \qquad (3)$$

where R is the heater resistance, C_p is the heat capacity of the shield, and t is the time allowed for the temperature change. The "proportional gain" A_p can be initially set via equation (3), then adjusted by trial and error to achieve maximum gain without oscillation.[7,8]

The ~~square of the~~ total voltage applied to the heater is therefore

$$V = V_{SS} + V_p \qquad (4)$$

If T_D is less than T_S, then the V is set to zero until T_D is attained. Cooling is such a slow process that "proportional" cooling is not necessary in our thermostat.

Figure 3 is a flow diagram of the control program, which is written in BASIC. The keyboard input allows the operator to enter the starting value of T_D, the desired temperature increments ΔT, the number of increments N, and the circulating cooler temperature T_A. If $T_D<T_S$, then no voltage is applied to the heater. If $T_D>T_S$, then a voltage calculated from equations 1-4 is applied to the heater. This determination of T_S relative to T_D is done repeatedly, at a sampling interval of about 20 sec. The control do-loop continues as long as $|T_D-T_S|>A$, where A

is on the order of millidegrees or $|T_S - T_E| > B$, where B is on the order of 10-100 millidegrees. TI is the running real time from the minicomputer clock. When $|T_D - T_S| < A$ and $|T_S - T_E| < B$, then control is maintained for a time C, after which the data are collected, T_D is incremented, and a new control loop begins.

IV. PERFORMANCE

A typical plot of the temperature at the radiation shield as a function of time while the feedback control is in operation is shown in Figure 4. It is clear that the deviations are less than 1 mK. The actual deviations at the experimental stage can be expected to be an order of magnitude smaller. The time constant of the thermostat is quite long. When T_A is about 10 K less than T_D, an increase of 1 K requires about 5 hours and a decrease of 1 K requires about 8 hours.

The control system does not seem to be particularly sensitive to any of the control parameters - the constants A_I and A_p or the sampling time. Typically A_I = 20 volts/deg and A_p = 40 volts/deg.

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18. Model PET 2001, Commodore Business Machines, Inc., Palo Alto, CA.

19. Model SN488-031, Kepco, Inc., Flushing, NY.

20. Model 1P-2728, Heath Co., Benton Harbor, MI.

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22. Model TNW-2000, TNW Corp., San Diego, CA.

FIGURE CAPTIONS

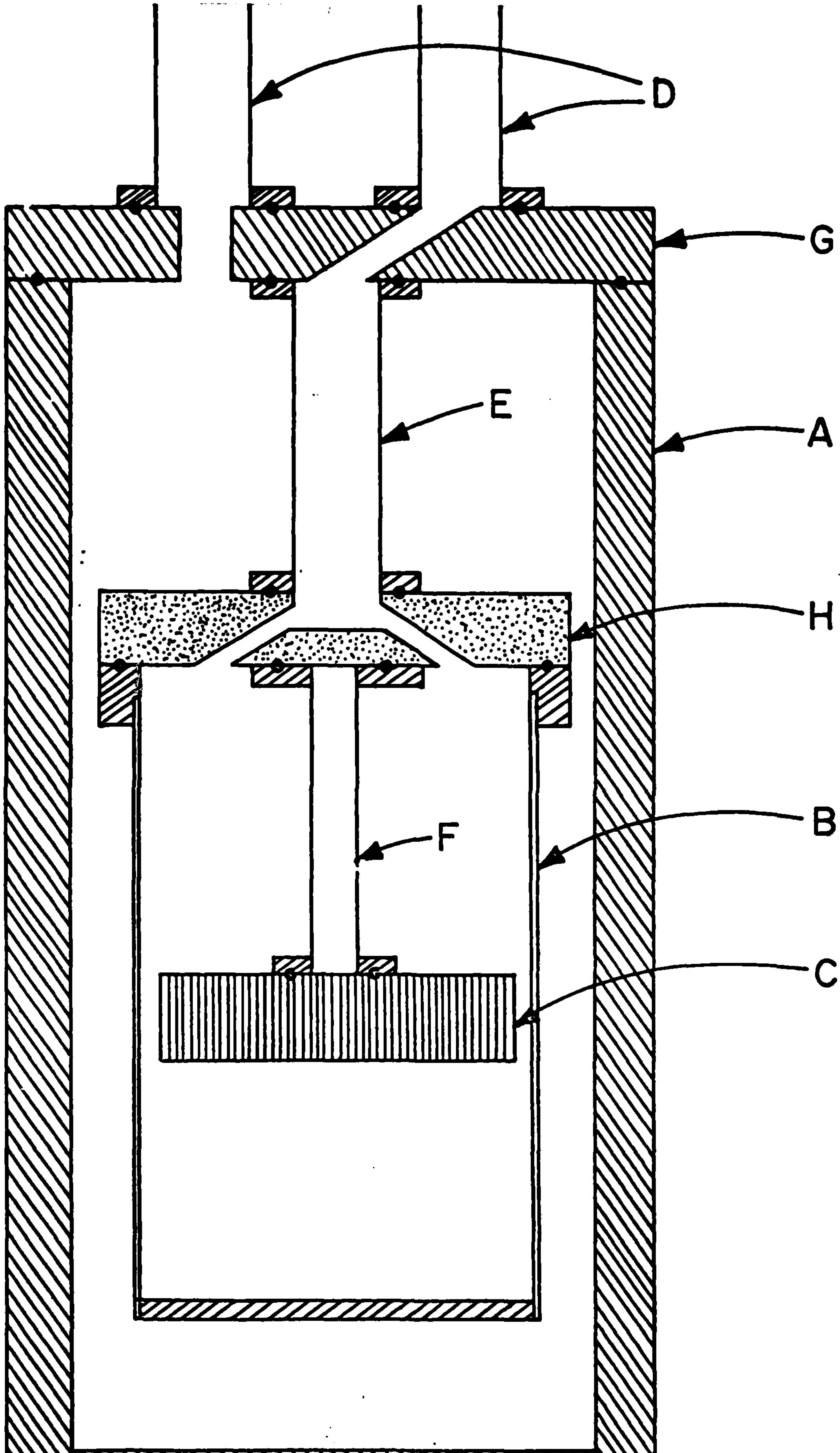
Fig. 1. Vacuum thermostat: A, outer vacuum can; B, inner vacuum can or radiation shield; C, experimental stage; D, vacuum lines; E and F, vacuum connections and supports for radiation shield and experimental stage; G and H, flanges. The drawing is to scale, with the outer vacuum can being 18 in. (45cm.) high.

Fig. 2. Hardware for temperature control and measurement system. T1 and T2 are resistance thermometers. R1 and R2 are standard resistors. The scanner and voltmeter read the voltage drops across T1, T2, R1, and R2. The computer calculates the temperature from the voltage drops, compares the actual temperatures to desired temperatures, then applies an appropriate voltage to the heater via the digital-to-analog converter and the programmable power supply.

Fig. 3. Flow diagram of computer program for temperature measurement and control. The symbols are: T_D, desired radiation shield temperature; N, number of do-loops which increment T_D by an amount ΔT; TI, running real time on computer clock; FG, flag to indicate when temperature first comes to desired value; T_S, actual radiation shield temperature; T_E, actual experimental stage temperature; V, voltage applied to heater; A, allowed difference between T_S and

T_E during control; B, allowed difference between T_D and T_S during control; C, equilibration time interval after control is achieved; H, real time at which data are to be collected.

Fig. 4. Temperature at the radiation shield as a function of time while under the control of the computer system. The temperature control at the experimental stage is probably considerably better.


D
G
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A
H
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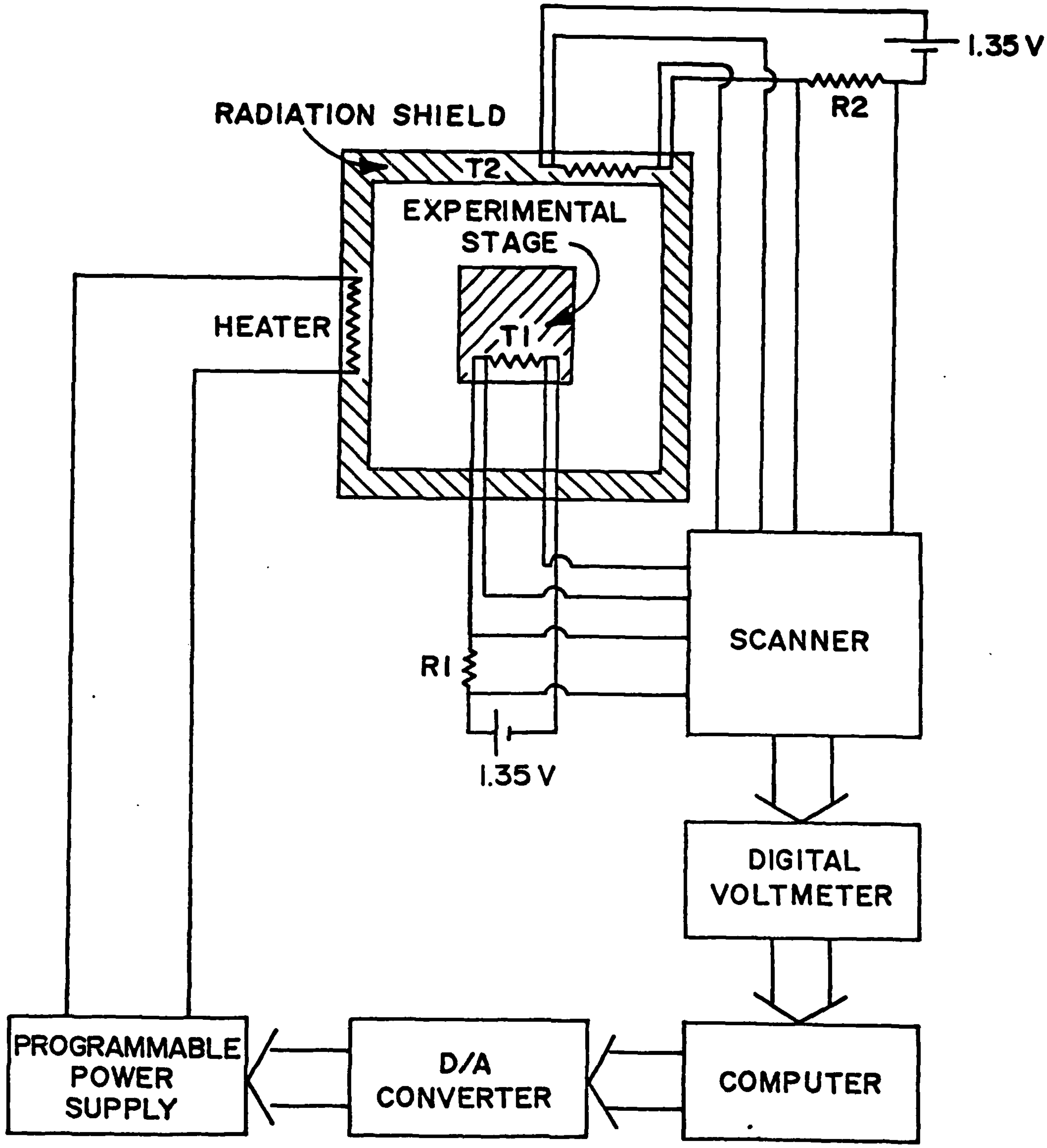
B
C


1.35 V
R2
RADIATION SHIELD
T2
EXPERIMENTAL
STAGE
HEATER
T1
SCANNER
R1
1.35 V
DIGITAL
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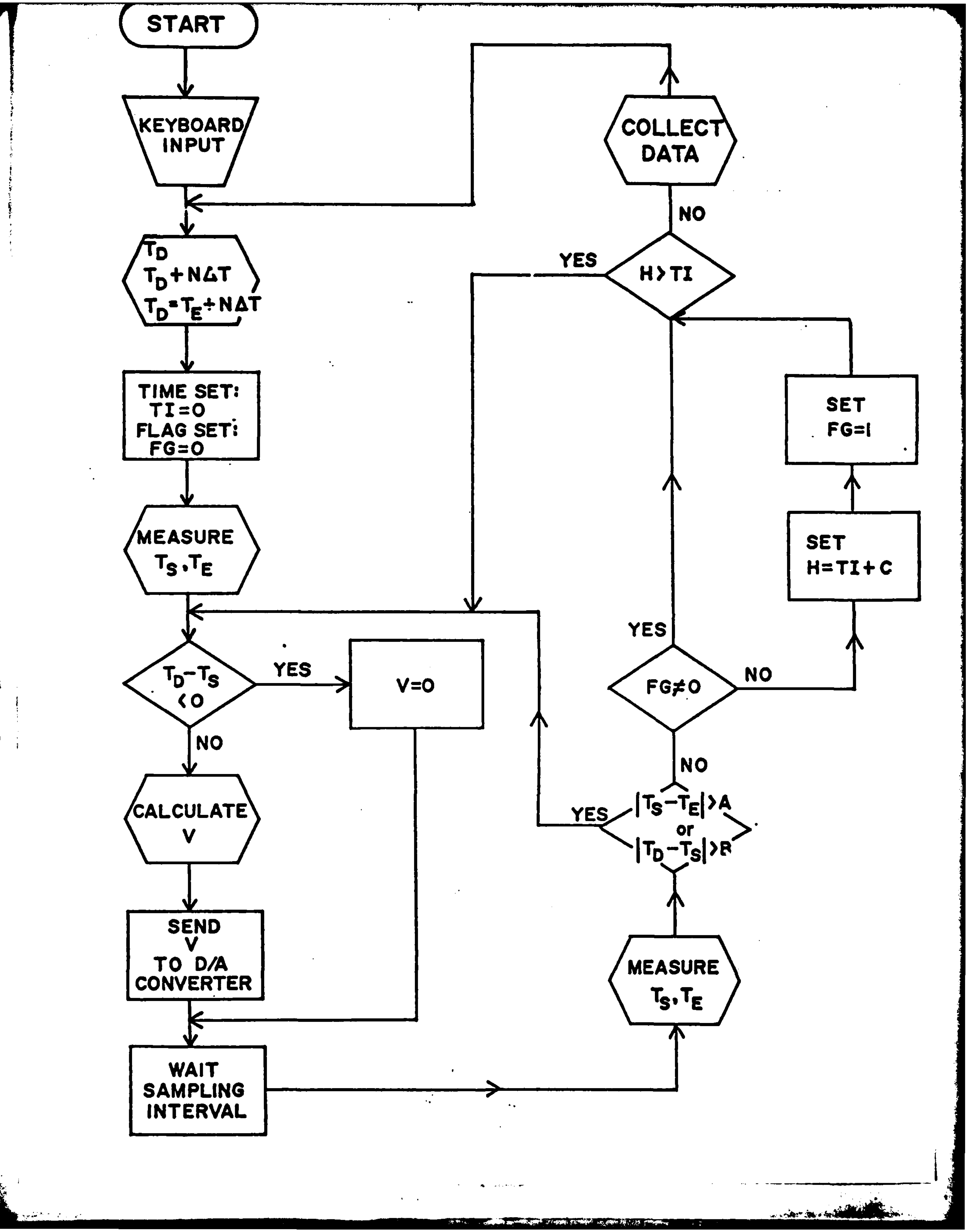
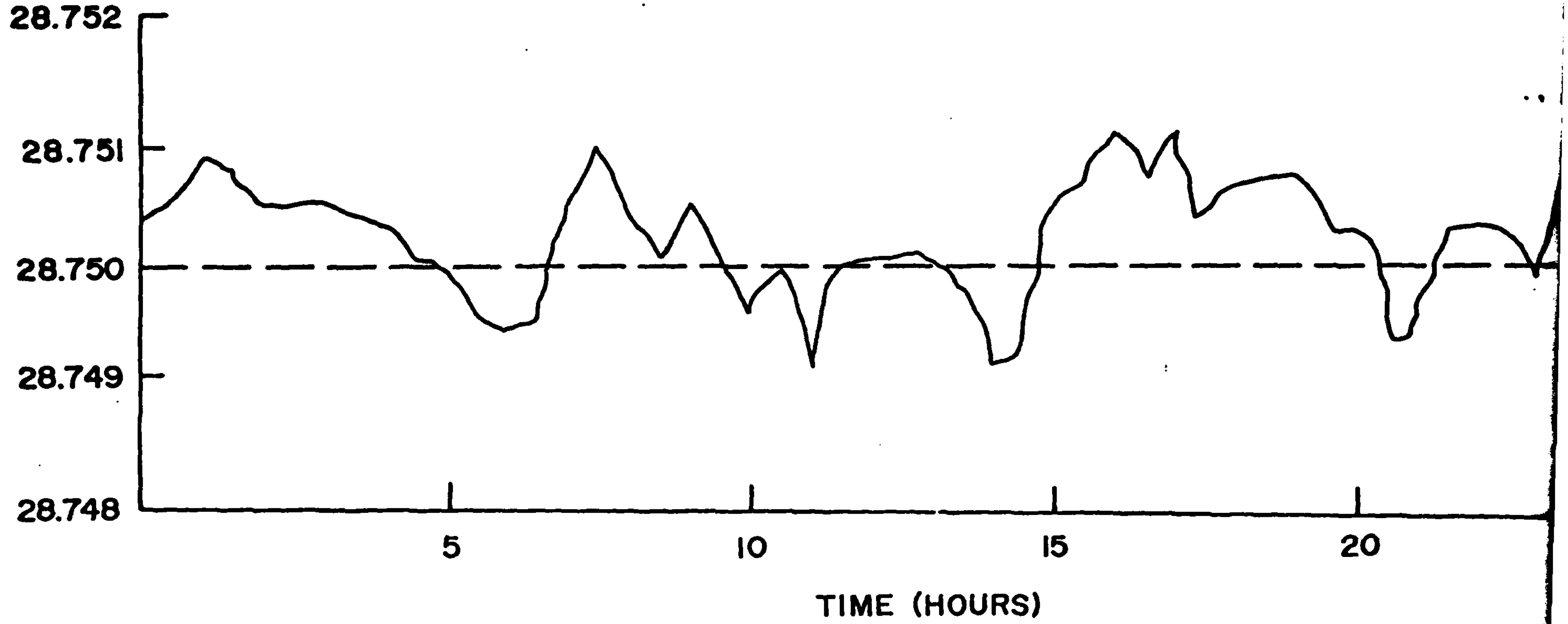
POWER
SUPPLY
D/A
CONVERTER
COMPUTER



START
KEYBOARD INPUT
T_D
$T_D + N\Delta T$
$T_D = T_E + N\Delta T$
TIME SET: TI=0
FLAG SET: FG=0
MEASURE T_S, T_E
$T_D - T_S < 0$
YES
NO
V=0
CALCULATE V
SEND V TO D/A CONVERTER
WAIT SAMPLING INTERVAL
MEASURE T_S, T_E
$|T_S - T_E| > A$ or $|T_D - T_S| > R$
YES
NO
FG≠0
YES
NO
SET H=TI+C
SET FG=1
H>TI
YES
NO
COLLECT DATA



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